PERGAMON

Vision Research 40 (2000) 3775–3781

Vision Research

www.elsevier.com/locate/visres

Variation in vernier acuity with age

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Received 29 October 1999; received in revised form 4 July 2000

Abstract

Many visual functions deteriorate with increasing age, vernier acuity apparently being an exception. We used an improved experimental protocol to investigate vernier thresholds in subjects in four age groups. Vernier threshold was found to increase with increasing age, and the difference in this, compared with previous findings is probably due to the smaller inter-pixel angle used. Vernier acuities in young subjects in other studies seem to have been underestimated. As vernier acuity did not vary with retinal illuminance and the sensitivity loss does not seem to be a learning effect, neural rather than optical changes are likely to account for the deterioration. Measurement of vernier acuity may have clinical application in the determination of visual function behind cataract, and it will be necessary to consider the effect of age on vernier acuity.

Keywords: Ageing; Vernier acuity; Vernier bias; Hyperacuity

1. Introduction

1.1. Visual functions and aging

Many visual functions decline with age. These include light detection (Weale, 1982), flicker sensitivity (Tyler, 1989), motion perception (Wood & Bullimore, 1995), visual acuity (Elliott, Whitaker, & Thompson, 1989; Elliott, Whitaker, & MacVeigh, 1990; Brown & Lovie-Kitchin, 1993; Elliott, Yang, & Whitaker, 1995; Rubin et al., 1997), both spatial and temporal contrast sensitivity (Owsley, Sekuler, & Siemsen, 1983; Owsley, Gardner, Sekuler, & Lieberman, 1985; Elliott, 1987; Elliott et al., 1990) and glare recovery (Collins, 1989). In part these changes are produced by deterioration in image quality in the elderly eye, mainly arising from reduced retinal illumination due to senile miosis (Kornzweig, 1954; Weale, 1961), increased lenticular absorption (Lerman, 1983), the reduced transmittance of the ocular media (Boettner & Wolter, 1962), and increased light scatter (Hemenger, 1984; IJspeert, de Waard, van den Berg, & de Jong, 1990).

Vernier stimulus configurations are little affected by optical disturbance of the retinal image and thus optical image degradation has only small effects on vernier performance (Williams, Enoch, & Essock, 1984; Vilar et al., 1995). Hence, vernier acuity measurement is useful in the evaluation of neural function of the visual system. Vernier acuity has been shown to be unaffected by cataract or by increased light scatter (Essock, Williams, Enoch, & Raphael, 1984). Vernier acuity is quite stable with respect to changes in contrast and luminance of the stimuli at suprathreshold levels (Leibowitz, 1955; Wehrhahn & Westheimer, 1990), therefore reduced retinal illuminance does not impose any difficulty for vernier alignment.

Odom, Vasquez, Schwartz, and Linberg (1989) reported that the vernier acuities in 55 subjects, aged 20–79 years, remain unchanged with increasing age, but that vernier bias increased sharply at about 35–45 years of age. However, the minimum displacement of the vernier stimulus in their experiment may have been too large (about 10 s of arc) to detect subtle changes in vernier measures. Moreover, they did not control the criterion used by their subjects in the determination of vernier offset.

Whitaker, Elliott and MacVeigh (1992) used the forced-choice staircase method (which does control the subject's criterion) to measure vernier thresholds for

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0042-6989/00/$ - see front matter
PII: S0042-6989(00)00212-1

2-line vernier stimuli with a vertical gap between the vernier features. They concluded that vernier acuity remains constant with increasing age, and that vernier bias and absolute vernier bias do not change with age. They suggested that the increased vernier bias in the elderly reported by Odom et al. (1989) might be due to methodological differences. Lakshminarayanan, Aziz and Enoch (1992) measured 2-dot vernier thresholds in 38 subjects aged 20–85 years. They reported that vernier acuity increases with gap size and that this gap function does not vary significantly with age. They also found no changes in vernier bias with increasing age. The method of adjustment they used is suitable for clinical use, but does not control the subject's criterion.

Lakshminarayanan and Enoch (1995) and Vilar et al. (1995) used a 3-dot vernier test array to study the effects of age on vernier measures. They asked subjects to adjust a central movable dot to align with the upper and lower reference dots. This test is simple to explain and easy for subjects to understand. Vernier performance with this arrangement is not affected by the subject's internal vertical sense or by head tilting (factors that may adversely affect testing using conventional 2-dot and 2-line test arrays), and the test is suitable for use in clinical settings. Vilar et al. (1995) found that the 3-dot vernier thresholds are less than the thresholds for a 2-dot test array, but, Lakshminarayanan et al. (1995) did not find any difference in performance between these tasks. Vilar et al. (1995) concluded that 2-dot and 3-dot vernier thresholds show little or no change with age. The minimum displacement of the vernier dots in this experiment, however, was 21 s of arc, a displacement that may have been too large to permit detection of subtle differences between age groups.

Other hyperacuities seem to be profoundly affected by increasing age. Buckingham, Whitaker and Banford (1987) and Elliott et al. (1989) have shown that the oscillatory movement displacement threshold increases with age, and that the rate of deterioration is proportional to age. These thresholds are also remarkably resistant to optical disturbance (Whitaker & Buckingham, 1987). In addition, displacement detection and

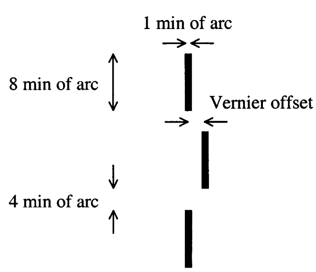

Fig. 1. Vernier stimulus used in the psychophysical measurements. The vernier stimulus actually consisted of three bright white rectangular patches of light against a dark background.

bisection thresholds are significantly increased in the elderly (Whitaker, Elliott, & MacVeigh, 1992). Stereoacuity is also reduced in older subjects (Hoffman, Price, Garrett, & Rothstein, 1959; Brown, Yap, & Fan, 1993).

1.2. Goals and characteristics of the present study

Given the uncertainties about vernier acuity and aging, and the expected parallels with other thresholds, the objectives of the current experiment were to re-examine the relationship between age and vernier acuity and to establish normative values.

In this experiment: (1) Vernier thresholds were measured in subjects aged 21–75 years. (2) Step sizes smaller than the expected thresholds were used, to permit a precise measure of vernier acuity. (3) Three-feature vernier stimuli were used, to eliminate the subject's internal vertical impression as a factor in measurement. (4) The method of constant stimuli was used to measure vernier acuity and vernier bias. (5) The 4 min of arc gap size in the target used results in a close-to-optimum vernier acuity in the presence of modest optical degradation (Williams et al., 1984). (6) The effect of reduced retinal illuminance on vernier acuity was examined in a control experiment.

2. Methods

2.1. Experimental set-up

The vernier stimulus consisted of three bright white rectangular patches of light (each subtending 1 min of arc by 8 min of arc) against a dark background (Fig. 1). The vertical separation between the segments was 4 min of arc. The flat 15-inch monitor screen was viewed monocularly from a distance of 6.5 m. The monitor resolution was 1280×1024 and the smallest inter-pixel visual angle was 6 s of arc. Room illumination in the laboratory was about 450 lux, and the luminance of the vernier stimulus was 240 cd/m^2. Light shielding was used to block the monitor screen from the stray light to increase the contrast of the stimulus.

The method of constant stimuli was used; three vernier lines presented to the subject were either in vertical alignment or the centre one was displaced laterally zero, one, two or three unit distances to the right or left, relative to the upper and lower vernier lines. In each trial, the position of the vernier element was randomly chosen from these seven settings, with the constraint that 40 trials were required for each setting. Forty responses were required in the initial demonstration and this was followed by the measurement session, which took about 30 min.

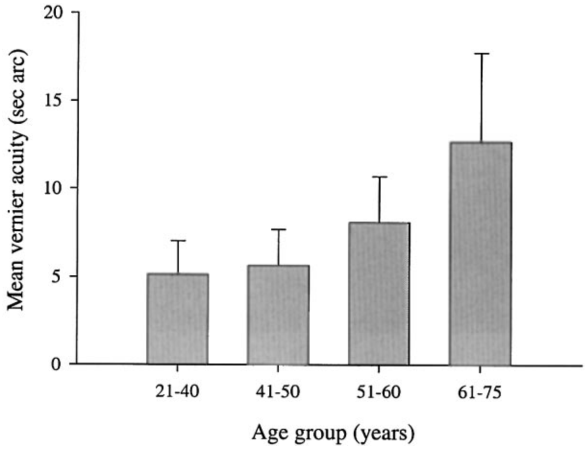

Fig. 2. Mean vernier acuities and S.D. bars for the four age groups. Vernier acuity was significantly reduced in the 61–75-year-old group.

Subjects were carefully refracted and their refractive errors were fully corrected. Vernier acuity was tested in the dominant eye only, the other eye being occluded. Subjects had their heads steadied by a chin rest and forehead bar. The subject's task was to say whether the middle line was to the right or to the left of the upper and lower reference lines on each presentation. The experimenter then input the response, and both auditory and visual feedback was given to the subject for each trial. These feedback systems were important for maintaining the subject's motivation in performing the task. The task was self-paced, to allow for the longer reaction time of elderly subjects.

Probit analysis (provided in SPSS 9.0) was used to determine the psychometric curve. The vernier acuity was defined as half the distance between the two offsets for which the responses were 25 and 75% 'to the right'. The vernier offset at which 50% responses 'to the right' were obtained represented the vernier bias, and this was the point of subjective equality. Vernier acuity provides a measure of the precision of alignment, while vernier bias indicates the accuracy or mean error of alignment.

2.2. Subjects

Sixty subjects were recruited, fifteen in each of four age groups: 21–40, 41–50, 51–60 and 61–75 years. Each group had seven male and eight female subjects. Preliminary eye examination was carried out in the Optometry Clinic of The Hong Kong Polytechnic University. The maculae of all subjects were assessed as normal; they had no drusen in an area of one disc diameter around the macula and no pigmentary changes in this area. All subjects had clear ocular media (as assessed by direct ophthalmoscopy) and were free of lens opacities in the dilated pupil area. They had no known visual problem (by self-report), and no subject had strabismus or amblyopia. All subjects had log MAR acuity of 0.0 (6/6) or better in both eyes; no letters on the 0.0 log MAR acuity line were missed. No subjects were experienced in psychophysical measurement.

The experiments were undertaken with the understanding and written consent of each subject and all procedures were approved via institutional review. The whole examination (vision screening plus vernier acuity measurement) took about 1 1/2 h.

2.3. Control experiment

It is well known that there is reduced retinal illuminance in the elderly eye, resulting from smaller pupil size and reduced ocular transmittance. The average pupil size is about 3 mm in older subjects (Wright & Drasdo, 1985; Sloane, Owsley, & Alvarez, 1988; Elliott et al., 1990). To eliminate these factors in their measures, Whitaker and Elliott (1992) measured contrast sensitivity in younger observers with miotic pupils (to simulate the senile miosis) and a 0.2 log unit neutral density filter (to simulate the increased light absorption by the ocular media), and concluded that there were neural changes in their older subjects. We performed a separate experiment to investigate the effect of reduced retinal illuminance on vernier acuity.

Eight subjects aged between 24 and 31 years (mean age: 26.25, S.D. = 2.60 years) were examined. Their natural pupil sizes were 5 mm or more. After they had participated in the first experiment, their vernier acuities were re-examined with a carefully centred 3-mm artificial pupil 10 mm from the cornea and with a neutral density filter (0.2 log unit).

3. Results

3.1. Vernier acuity and age

Mean vernier acuities were 5.1, 5.7, 8.1 and 12.6 s of arc, for the 21–40-, 41–50-, 51–60- and 61–75-year-old subject groups respectively (Fig. 2). The S.D. of the means also increased with increasing age (1.9, 2.0, 2.6 and 5.2 s of arc for the four age groups). Vernier acuities and S.E. bars for individuals are shown in Fig. 3. A bi-linear regression model, shown below, was developed using SigmaPlot 4.01 to fit the data. Before the age of 50 years, the slope of the linear regression line is nearly zero, and afterwards vernier threshold increases linearly by 0.42 s of arc per year ($r^2 = 0.51$).

$$y = 0.01\ (\text{S.E.} = 0.06) \times [x - 49.50\ (\text{S.E.} = 3.84)] + 5.52\ (\text{S.E.} = 1.00)$$

(from 21 to 50 years)

$$y = 0.42\ (\text{S.E.} = 0.09) \times [x - 49.50\ (\text{S.E.} = 3.84)] + 5.52\ (\text{S.E.} = 1.00)$$

(from 50 to 75 years)

Vernier acuity was significantly reduced after the age of 60 years. There was a statistically significant difference in vernier acuity between the subject groups (ANOVA: $F = 17.26$; df = 3.56; $P < 0.0001$). Post-hoc testing with the Tukey–Kramer test revealed significant differences between the 21–40- and 61–75-year-old subjects ($q = 9.10$; $P < 0.001$), between the 41–50- and 61–75-year-old subjects ($q = 8.48$; $P < 0.001$), and between the 51–60- and 61–75-year-old subjects ($q = 5.53$; $P < 0.01$), but there were no significant differences between the other age groups ($q = 2.95$ or less, $P > 0.05$ in all cases).

3.2. Vernier bias and age

Because the magnitude of vernier bias was of interest in the present experiment, the absolute value of vernier bias (Fig. 4) was used to indicate the mean error of misalignment. There was no significant difference in the absolute vernier bias in the four age ranges (ANOVA: $F = 1.42$; df = 3.56; $P = 0.25$). Mean absolute vernier biases and S.D. for the four groups were 2.1 (S.D. = 1.3), 1.7 (S.D. = 2.0), 1.6 (S.D. = 1.1) and 2.9 (S.D. = 2.6) s of arc, for the 21–40-, 41–50-, 51–60- and 61–75-year-old subject groups respectively.

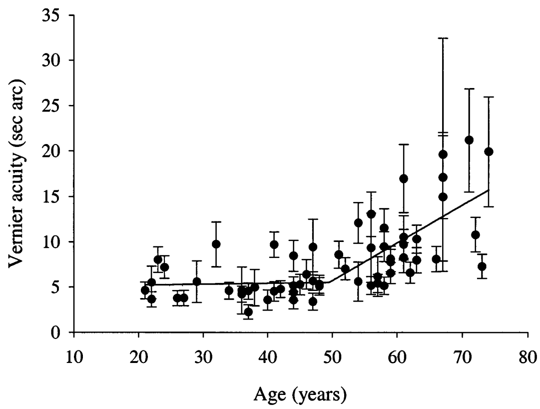

Fig. 3. Vernier acuity as a function of age for individual observers.

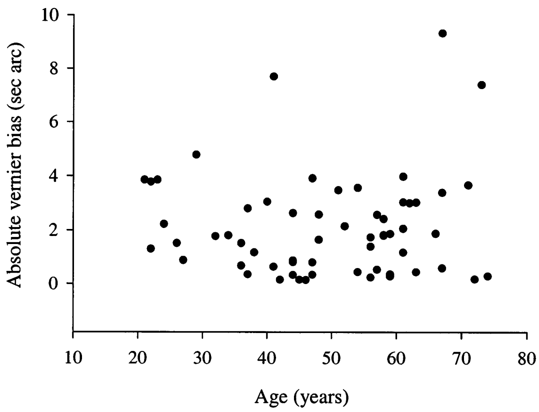

Fig. 4. Absolute vernier bias for individual observers as a function of age.

3.3. Control experiment

Vernier acuity was minimally affected by reduced retinal illuminance when compared to that measured with and without pinhole and filter. The mean vernier acuity measured with natural pupil was 5.26 s arc (S.D. = 1.65), and that measured with pinhole and filter was 5.79 s of arc (S.D. = 1.37). There was no significant difference in the vernier acuity measured without and with pinhole and filter (paired t-test: $t = 2.18$; df = 7; $P = 0.07$).

4. Discussion

4.1. Vernier acuity and age

Three-line vernier acuity was significantly worse after the age of about 60 years, with thresholds increasing from 5.1 s of arc in the youngest group to 12.6 s of arc in the oldest group. All subjects in this study were free of ocular anomalies, with normal maculae and good visual acuity (log MAR acuity of 0 or better) and were not amblyopic. Moreover, vernier acuity is minimally affected by optical degradation (Williams et al., 1984), so that the sensitivity loss is presumably due to neural loss between retina and cortex.

Contrary to the findings of previous researchers, the precision of localization was significantly reduced in our elderly subjects. The vernier thresholds of our subjects aged above 60 years seem comparable with those reported by Odom et al. (1989), Whitaker et al. (1992) and Vilar et al. (1995), which ranged from 8 to 20 s of arc. In contrast, our young adults aged 20–50 years had much better vernier acuity, by a factor of about two. The vernier acuities in the young subjects in other studies seem to have been underestimated. This is probably because of the differences in methodology, since our study used a much smaller inter-pixel visual angle, thus allowing much smaller vernier acuity values to be measured. Moreover, the use of a 3-line stimulus that clarifies subject's impression of vertical along with feedback system lead to improved vernier thresholds.

The minimum horizontal displacement of the vernier line adopted by Odom et al. (1989) was 10 s of arc, and this is probably not small enough to measure vernier acuity in young adults. The resolution of the monitor used by Vilar et al. (1995) was 640 × 480, so that at the 4 m viewing distance they used, the minimum step size was 21 s of arc. Lakshminarayanan et al. (1992) did not mention the step size used, but the short-viewing distance (1.5 m) is likely to have resulted in large step sizes. Whitaker et al. (1992) did not report their step size or the resolution of the display used in their experiments. Vernier stimuli can be positioned with an accuracy that exceeds the pixel resolution of the display used to produce them (Morgan & Aiba, 1985; Georgeson, Freeman, & Scott-Samuel, 1996), however, none of these studies used graphical manipulation to allow sub-pixel positioning of stimuli.

A small step size is a pre-requisite for accurate measurement of vernier acuity. The vernier acuities for young and older subjects in our experiment were about 5 and 13 s of arc respectively. Had the step size been 21 s of arc (as in the Vilar et al. (1995) experiment), thresholds for both young and older subjects would be well within one unit of the vernier line displacement. Differences in performance between young and elderly subjects only became apparent for smaller vernier offsets.

Other hyperacuities such as displacement detection and bisection thresholds are also affected by increasing age (Buckingham, Whitaker, & Banford, 1987; Whitaker et al., 1992). In addition, the oscillatory movement displacement threshold increases with increasing age (Buckingham et al., 1987; Elliott et al., 1989). Brown et al. (1993) showed that stereoacuity is adversely affected with advancing age by using a step size smaller than had been used previously.

Figs. 2 and 3 show that there is much greater variance in vernier acuity in older than in younger subjects. The decrease in vernier acuity in later life therefore may not be a ubiquitous phenomenon. In our data there appear to be two kinds of older subjects: those whose vernier thresholds were dramatically elevated and those whose vernier thresholds were only slightly elevated relative to the younger subjects. The factors differentiating these two groups of older subjects remain unclear, but it is important to recognize the role of individual differences. Moreover it is not uncommon to find greater variation of visual thresholds in older subjects (Buckingham et al., 1987).

Absolute vernier bias was unaffected by age, supporting the findings of Lakshminarayanan et al. (1992) and Whitaker et al. (1992). It is reasonable to expect that the point of subjective equality does not change significantly with age, if, as suggested by Weale (1982), there is no uneven distortion of the neuro-visual system. However, it is still not clear whether vernier bias is the result of neural asymmetry or a variable internal 'impression of verticality'. The feedback provided to the subjects in the present study may alter the observer's responses, and thus reduce any bias in subjective judgments of localization, and this may cause difficulty in finding alternations in vernier bias with age.

4.2. Neural changes

It is well recognized that optical and neural changes play an important role in the deterioration of visual performance with age. Contrast sensitivity loss in older subjects in good eye health is largely attributable to optical factors (Burton, Owsley, & Sloane, 1993). Senile miosis and reduced transmittance of ocular media in the elderly decrease the retinal illuminance, however we found that reduced retinal illuminance in younger subjects had minimal effects on vernier acuity. In addition, the vernier stimulus configuration selected for the current experiment results in close-to-optimum threshold in the presence of modest optical degradation (Williams et al., 1984), and vernier alignment is little affected by changes in contrast and luminance of stimuli at suprathreshold levels (Leibowitz, 1955; Wehrhahn & Westheimer, 1990). It is thus not unreasonable to suggest that the reduction of vernier acuity in our older subjects is neural in origin.

It is well known that practice improves performance on vernier acuity tasks (McKee & Westheimer, 1978; Fahle & Edelman, 1993). It might be argued that older subjects had more difficulty learning the task than did our younger subjects. To address this issue, we had one of the older subjects repeat the vernier acuity measurements a further three times, under identical conditions. This subject was an experienced observer and familiar with vernier acuity measurement and had given more than three thousand responses in another vernier acuity experiment. This 69-year-old subject had vernier acuity values of 19.86 (S.E. = 5.00), 18.18 (S.E. = 4.21) and 17.83 s (S.E. = 4.06) arc, representing improvements of 8 and 10% after two and three sessions respectively and improvement of 20% in error estimate with practice; final thresholds were still more than three times those of the younger subjects.

It is not unexpected that neural changes at the retinal and cortical levels may result in reduction of visual function. Although our older subjects had log MAR visual acuity of 0 or better, we cannot rule out retinal change completely, since visual acuity gradually decreases with increasing age (Brown & Lovie-Kitchin, 1993; Elliott et al., 1995; Rubin et al., 1997). There may be a loss of about 0.1 log MAR in our elderly subjects, which could contribute to some of the loss in vernier acuity. Histological evidence tends to support the gradual loss of retinal substrate with increased age. While earlier studies reported a net loss of foveal cone cells in subjects older than 40 years (Gartner & Henkind, 1981; Marshall, 1987), some studies have found no significant loss of foveal cone cells up to the age of 90 years (Gao & Hollyfield, 1992; Curcio, Millican, Allen, & Kalina, 1993). In contrast, there is a steady decrease in the number of rods in the central retina with increasing age (Curcio et al., 1993). About 50% of retinal ganglion cells are lost in patients older than 70 years, and of these 50% are estimated to be responsible for macular function (Marshall, 1987). There is also a loss and displacement of cell nuclei in the outer nuclear layer (Gartner & Henkind, 1981). The concentration of lipofuscin in retinal pigment epithelium increases gradually with age, and more rapidly after 60 years of age (Tucker, 1986; Iwasaki & Inomata, 1988), and these incompletely degraded particles may decrease cellular metabolic activity.

The number and functional quality of cortical neurons decrease with age, and these changes may play a role in the loss of accuracy in vernier alignment. Devaney and Johnson (1980) reported that up to 54% of cortical neurons are lost with increasing age, and Weale (1982) has suggested that such cell loss is random. Moreover, the number of dendritic spines decreases in aging cortical cells (Scheibel, Lindsay, Tomisayu, & Scheibel, 1975). It appears that many neural components are compromised to some extent and these changes lead to a general neural processing loss. For example, visual evoked potentials show decreased amplitude and prolonged latency in older subjects (Synder, Dustman, & Shearer, 1981; Allison, Hume, Wood, & Goff, 1984; Wright, Williams, Drasdo, & Harding, 1985; Tomoda, Celesia, Brigell, & Toleikis, 1991; Tobimatsu, 1995). These electrophysiological studies provide evidence of age-related functional loss at the level of the primary visual cortex.

4.3. Clinical significance

The present findings serve as baseline data for measures of vernier threshold as a function of age. The availability of age norms for both vernier acuity and vernier bias should provide the basis for further development of this specialized, yet potentially very useful, tool for clinical assessment. For vernier acuity in clinical situations (Enoch, Williams, Essock, & Barricks, 1984; Essock et al., 1984; Enoch, Williams, Essock, & Fendick, 1985; Essock, Enoch, Williams, Barricks, & Raphael, 1985; Enoch, Baraldi, Lakshminarayanan, Savage, & Fendick, 1988; Enoch, 1992; Enoch et al., 1995; Enoch & Knowles, 1995), the thresholds of patients should be compared to those of age-matched normal groups, so as to minimize the contaminating effects of aging.

Acknowledgements

The authors thank Dennis Levi and Stanley Klein for their useful comments on the work, and their advice on the control experiments. We also thank them for their suggestions on analysis and presentation of the data. We should like to thank the reviewers for their very useful comments on this manuscript. This work was supported by a research grant from The Hong Kong Polytechnic University (V302).

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